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SEMI-ANNUAL STATUS REPORT

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for

1 April 1986 - 30 September 1986

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SEMI-ANNUAL STATUS REPORT

NASA Grant NGR 05-002-160

Space Radiation Laboratory (SRL)
California Institute of Technology

1 April 1986 - 30 September 1986

This report covers the research activities in Cosmic Rays, Gamma Rays, and Astrophysical Plasmas supported under NASA Grant NGR 05-002-160. The report is divided into sections which describe the activities, followed by a bibliography.

This group's research program is directed toward the investigation of the astrophysical aspects of cosmic rays and gamma rays and of the radiation and electromagnetic field environment of the Earth and other planets. We carry out these investigations by means of energetic particle and photon detector systems flown on spacecraft and balloons.

1. Particle Astrophysics

This research program is directed toward the investigation of galactic, solar, interplanetary, and planetary energetic particles and plasmas. The emphasis is on precision measurements with high resolution in charge, mass, and energy. The main efforts of this group, which are supported partially or fully by this grant, have been directed toward the following two categories of experiments.

1.1. Activities in Support of or in Preparation for Spacecraft Experiments

These activities generally embrace prototypes of experiments on existing or future NASA spacecraft or they complement and/or support such observations.

1.1.1. The High Energy Isotope Spectrometer Telescope (HEIST)

HEIST is a large-area ($0.25 \text{ m}^2 \text{sr}$) balloon-borne isotope spectrometer designed to make high resolution measurements of isotopes in the element range from H to Ni ($1 \leq Z \leq 28$) at energies from ~ 0.4 to 2.0 GeV/nucleon . The instrument consists of a stack of 12 NaI(Tl) scintillators (L1 to L12) of total thickness 88 g/cm^2 , two Cerenkov counters (C1 and C2), and two plastic scintillators (S1 and S2) as illustrated in Figure 1. Each of the 2-cm thick NaI disks is viewed by six 1.5-inch photomultipliers (PMTs) whose combined outputs measure the energy deposition in that layer. In addition, the six outputs from each disk are compared to determine the position at which incident nuclei traverse each layer to an accuracy of $\sim 2 \text{ mm}$.

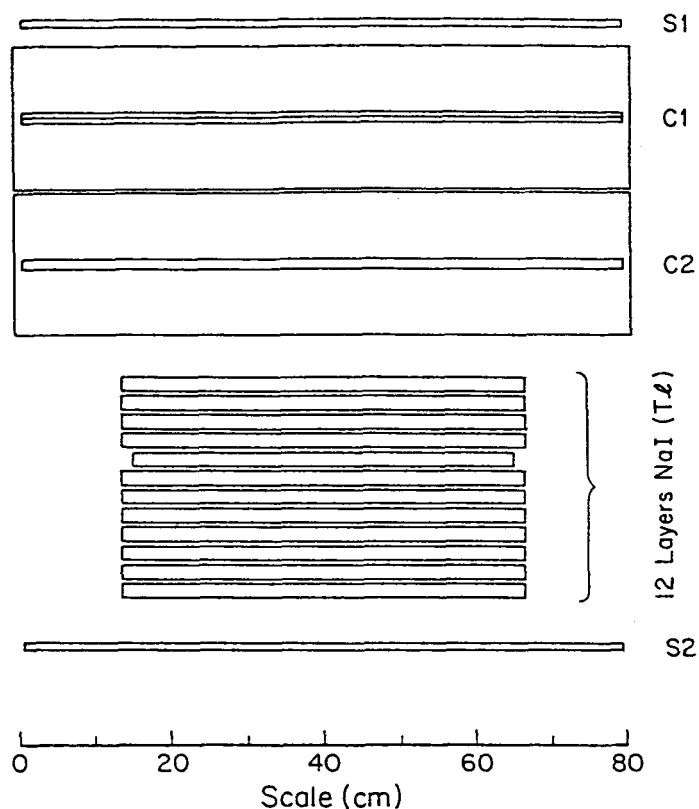


Figure 1

The Cerenkov counters, which measure particle velocity, are each viewed by twelve 5-inch photomultipliers using light integration boxes. This experiment is a collaborative effort with the Danish Space Research Institute and the University of New Hampshire.

HEIST determines the mass of individual nuclei by measuring both the change in the Lorentz factor ($\Delta\gamma$) that results from traversing the NaI stack, and the energy loss (ΔE) in the stack. Since the total energy of an isotope is given by $E = \gamma M$, the mass M can be determined by $M = \Delta E / \Delta\gamma$. The instrument is designed to achieve a typical mass resolution of 0.25 amu.

The energy range covered by HEIST can be "tuned" by choice of the index of refraction (n) of the two Cerenkov counters. In its present configuration (HEIST-2, shown in Figure 1) C1 is composed of Teflon ($n = 1.33$) and C2 is fused silica ($n = 1.50$) and the instrument is capable of resolving isotopes from Be to Ni over the energy range from ~ 0.4 to ~ 1.1 GeV/nucleon, as shown in Figure 2. In HEIST-2 the Cerenkov counters provide independent measurements of the velocity, leading to two independent measurements of the mass of incident nuclei which stop in the NaI stack. Thus, HEIST-2 is designed to provide improved mass resolution and yield over the initial version of the instrument (HEIST-1, see below).

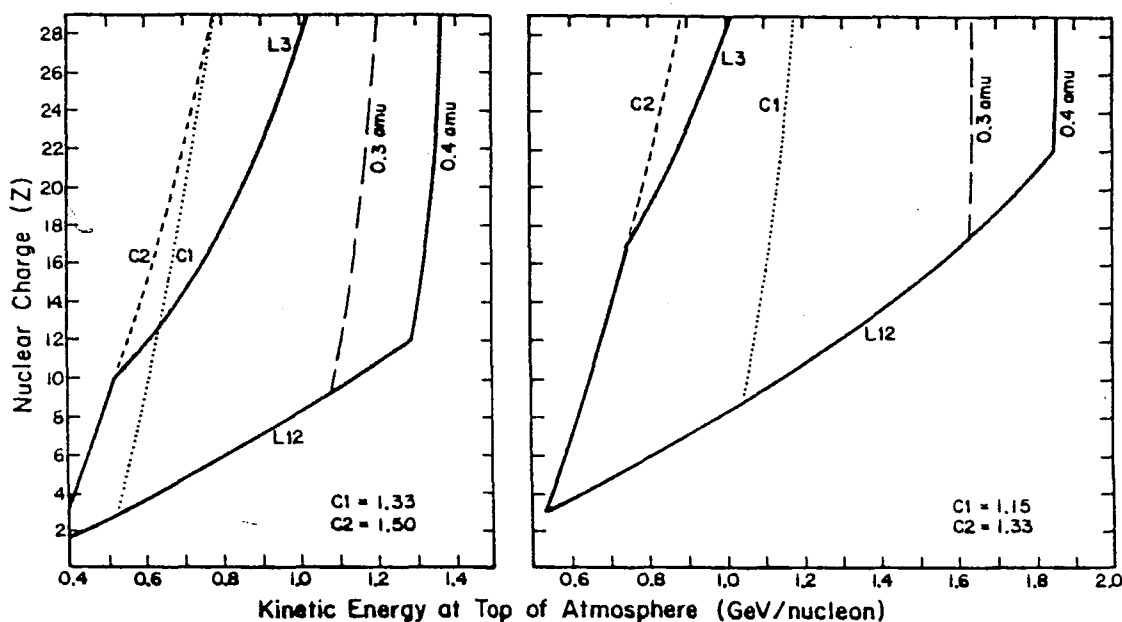


Figure 2

The new Cerenkov counters for HEIST-2 were developed in collaboration with W. R. Webber of the University of New Hampshire (UNH). Specifically, New Hampshire provided two light integration boxes, complete with sixteen 5" photomultipliers viewing each box, and a large disk (80 cm diam) of fused silica for the C2 radiator. In addition, we have been collaborating with New Hampshire in the development of improved wave-shifting techniques, and on new high-reflectance paints for the light integration boxes. Caltech has been responsible for developing the Teflon radiator for the C2 counter, for machining the fused silica disk, for wave-shifting the radiators, and for repainting and modifications of the light integration boxes. We have also been responsible for testing and optimizing the light output of the counters which has resulted in considerable progress in several areas of Cerenkov counter development. In particular, improvements were made in wave-shifting, and high-reflectance painting techniques, and a new teflon "sandwich" radiator was developed that optimizes the output of C1. These developments were reported in our last progress report. Other improvements in HEIST-2 include a commandable high-gain mode, normally used for testing with ground-level muons, that can be used in flight to provide measurements of H and He isotopes with several hundred MeV/nucleon.

HEIST-2 was readied for balloon flight during the early summer of 1986 and was shipped to Ainsworth, Nebraska where it successfully passed final preflight tests. HEIST was launched on September 7, 1986 on a $23 \times 10^6 \text{ ft}^3$ Winzen balloon. The instrument was turned on shortly after launch and began recording heavy nuclei. Data received indicated that all systems were

operating normally and that the newly designed trigger system was successful in reducing the event background due to He nuclei. Unfortunately, at an altitude of $\sim 70,000$ ft the balloon burst catastrophically. The package parachuted to earth but suffered some damage to the pressure vessel, to the top scintillator, and to the top Cerenkov counter, when it was pulled over on its side upon landing. HEIST was then returned to our laboratory where it is now undergoing repair in preparation for another launch this coming summer.

HEIST-2 is an outgrowth of an earlier version of the instrument (HEIST-1) which was successfully flown from Palestine, Texas in May 1984. In HEIST-1 the top Cerenkov counter was composed of aerogel ($n = 1.1$) while the bottom Cerenkov counter (a Teflon and Pilot-425 combination) was located beneath the NaI stack to allow isotope studies of nuclei that passed entirely through the NaI stack. The energy range for HEIST-1 was ~ 1.5 to 2.0 GeV/nucleon.

The analysis of data from the 1984 flight is proceeding. A great deal of effort has gone into the development and optimization of methods to determine the position and energy-loss of ions traversing the NaI stack. The algorithms depend on detailed maps of each PMT viewing the NaI, as derived from the ^{55}Mn Bevalac calibration of HEIST. Our position determining algorithm presently achieves $\sim 2\text{mm}$ (rms) resolution in each layer, while the energy loss resolution of each layer is $\sim 1\%$ (rms).

We have recently been concentrating our data analysis efforts on mapping the response of the aerogel Cerenkov counter. In particular, we are attempting to isolate the various contributions to the Cerenkov resolution including photoelectron statistics, index of refraction variations, and fluctuations in the Cerenkov light produced by delta rays. Fits to the response at three different beam energies give an rms variation in the index of refraction of $\sigma_n/n = 0.0003$, which would contribute ~ 0.1 amu to the mass resolution of ^{56}Fe nuclei, and a lesser amount to lighter elements in proportion to their mass.

In addition to our work on HEIST, we have also devoted considerable effort recently to the defining the goals and capabilities of Astromag, the proposed superconducting magnet facility for particle astrophysics on the space station. The following recent talks and papers have resulted from this work:

- "ASTROMAG: The Particle Astrophysics Magnet Facility", Interim Report of the Astromag Definition Team. Editors: J. F. Ormes, M. Israel, M. Wiedenbeck, and R. Mewaldt (1986).
- "ASTROMAG: A Superconducting Particle Astrophysics Magnet Facility for the Space Station", M. A. Green et al., to be published in *IEEE*, (1986).
- "Measurements of Cosmic Ray Isotopes with a Super-Conducting Magnet Facility", R. A. Mewaldt, *Proceedings of the Workshop on Scientific Uses of the Space Station in Cosmic Ray and High Energy Gamma-Ray Physics*, J. Klarmann, editor, Washington University, St. Louis, MO (1985).

1.1.2. Low Energy Isotope Spectroscopy

In April of 1986 we responded on very short notice to a request from NASA Headquarters to propose low-cost experiments that might be launched by a Scout rocket into low-Earth orbit. We proposed two possibilities: 1) The unfinished COMPAS experiment that we were developing jointly with Goddard, Maryland, MPI and New Hampshire for the US spacecraft of

the ISPM mission until this spacecraft was canceled in late 1981; 2) the ACE experiment described in Section 1.2.5. During the next few months we studied the first option (COMPAS) in more detail and provided additional information for a study being conducted by Goddard Space Flight Center on this and other possible low-cost missions.

COMPAS consists of five sensors designed to determine the isotopic and elemental composition of energetic particles from ~ 40 keV/nucleon to ~ 400 MeV/nucleon. A key element of COMPAS is the MAST telescope that was being built by our group to measure the elemental and isotopic composition of galactic cosmic rays, the anomalous cosmic rays, and solar energetic particles.

In the course of this study it was determined that all or part of COMPAS could be accommodated by a Scout launch and available spacecraft with only minor modifications. Although a low-altitude Earth-orbit is not as desirable as being in interplanetary space, with a polar orbit MAST could provide a collecting power for the isotopes of low energy galactic cosmic rays, and solar particles exceeding that of all previous experiments.

1.2. Experiments on NASA Spacecraft

The SR&T grant program of the Space Radiation Laboratory is strengthened by and contributes to the other programs described here. Activities related to these programs are primarily funded by mission-related contracts but grant funds are used to provide a general support base and the facilities which make these programs possible.

1.2.1. An Electron/Isotope Spectrometer (EIS) Launched on IMP-7 on 22 September 1972 and on IMP-8 on 26 October 1973

This experiment is designed to measure the energy spectra of electrons and positrons (0.16 to ~ 6 MeV), and the differential energy spectra of the nuclear isotopes of hydrogen, helium, lithium, and beryllium (~ 2 to 50 MeV/nucleon). In addition, it provides measurements of the fluxes of the isotopes of carbon, nitrogen, and oxygen from ~ 5 to ~ 15 MeV/nucleon. The measurements from this experiment support studies of the origin, propagation, and solar modulation of galactic cosmic rays; the acceleration and propagation of solar flare and interplanetary particles; and the origin and transport of energetic magnetospheric particles observed in the plasma sheet, adjacent to the magnetopause, and upstream of the bow shock.

The extensive EIS data set has been utilized in comprehensive studies of solar, interplanetary, and magnetospheric processes. Correlative studies have involved data from other IMP investigations and from other spacecraft, as well as direct comparisons of EIS data from IMP-7 and IMP-8.

During the past year our studies of IMP data have resulted in the following papers:

- “ ^3He in Galactic Cosmic Rays,” R. A. Mewaldt, *Ap. J.* **311**, 979-983 (1986).
- “A Re-Examination of the Cosmic Ray Helium Spectrum and the $^3\text{He}/^4\text{He}$ Ratio at High Energies,” W. R. Webber et al., *To be published in Ap.J.* (1986).
- “Solar Cycle Variations of Anomalous ^4He as Revealed by Studies of Cosmic Ray ^3He ,” A. C. Cummings et al., *Bull. of Am. Phys. Soc.* **31**, 872 (1986).

1.2.2. An Interstellar Cosmic Ray and Planetary Magnetospheres Experiment for the Voyager Missions Launched in 1977

This experiment is conducted by this group in collaboration with F. B. McDonald and J. H. Trainor (Goddard Space Flight Center), W. R. Webber (University of New Hampshire), and J. R. Jokipii (University of Arizona), and has been designated the Cosmic Ray Subsystem (CRS) for the Voyager Missions. The experiment is designed to measure the energy spectra, elemental and (for lighter elements) isotopic composition, and streaming patterns of cosmic-ray nuclei from H to Fe over an energy range of 0.5 to 500 MeV/nucleon and the energy spectra of electrons with 3 - 100 MeV. These measurements will be of particular importance to studies of stellar nucleosynthesis, and of the origin, acceleration, and interstellar propagation of cosmic rays. Measurements of the energy spectra and composition of energetic particles trapped in the magnetospheres of the outer planets are used to study their origin and relationship to other physical phenomena and parameters of those planets. Measurements of the intensity and directional characteristics of solar and galactic energetic particles as a function of the heliocentric distance will be used for *in situ* studies of the interplanetary medium and its boundary with the interstellar medium. Measurements of solar energetic particles are crucial to understanding solar composition and solar acceleration processes.

The CRS flight units on both Voyager spacecraft have been operating successfully since the launches on August 20, 1977 and September 5, 1977. The CRS team participated in the Voyager 1 and 2 Jupiter encounter operations in March and July 1979, and in the Voyager 1 and 2 Saturn encounters in November 1980 and August 1981; and in the Voyager 2 Uranus encounter in January 1986. The Voyager data represent an immense and diverse data set, and a number of scientific problems are under analysis. These investigation topics range from the study of galactic particles to particle acceleration phenomena in the interplanetary medium to plasma/field energetic particle interactions, to acceleration processes on the sun, to studies of elemental abundances of solar, planetary, interplanetary, and galactic energetic particles, and to studies of particle/field/satellite interactions in the magnetospheres of Jupiter and Saturn.

The following publications and papers for scientific meetings, based on Voyager data, were generated:

- "Energetic Charged Particles in the Uranian Magnetosphere," E. C. Stone et al., *Science* **233**, 93-97 (1986).
- "Evidence for a Latitudinal Gradient of the Cosmic Ray Intensity," S. P. Christon et al., *Geophys. Res. Ltrs.* **13**(8), 777-780 (1986).
- "The Voyager 2 Encounter with the Uranian System," E. C. Stone and E. D. Miner, *Science* **233**, 39-43 (1986).
- "Solar Cycle Variations of Anomalous ^4He as Deduced by Studies of Cosmic Ray ^3He ," A. C. Cummings et al., *Geophys. Res. Ltrs.* **13**(10), 1043-1046 (1986).
- "Solar Cycle Variations of Anomalous ^4He as Revealed by Studies of Cosmic Ray ^3He ," A. C. Cummings et al., *Bull. of Am. Phys. Soc.* **31**, 872 (1986).

1.2.3. A Heavy Isotope Spectrometer Telescope (HIST) Launched on ISEE-3 in August 1978

HIST is designed to measure the isotope abundances and energy spectra of solar and galactic cosmic rays for all elements from lithium to nickel ($3 \leq Z \leq 28$) over an energy range from several MeV/nucleon to several hundred MeV/nucleon. Such measurements are of importance to the study of the isotopic constitution of solar matter and of cosmic ray sources, the study of nucleosynthesis, questions of solar-system origin, studies of acceleration processes and studies of the life history of cosmic rays in the galaxy.

HIST was successfully launched on ISEE-3 and provided high resolution measurements of solar and galactic cosmic ray isotopes until December 1978, when a component failure reduced its isotope resolution capability. Since that time, the instrument has been operating as an element spectrometer for solar flare and interplanetary particle studies.

Our work on solar flare, interplanetary, and galactic cosmic ray isotopes has resulted in the following recent talks and papers.

- “ ^3He in Galactic Cosmic Rays,” R. A. Mewaldt, *Ap. J.* **311**, 979-983 (1986).
- “A Re-Examination of the Cosmic Ray Helium Spectrum and the $^3\text{He}/^4\text{He}$ Ratio at High Energies,” W. R. Webber et al., *To be published in Ap.J.* (1986).

1.2.4. A Heavy Nuclei Experiment (HNE) Launched on HEAO-C in September 1979

The Heavy Nuclei Experiment is a joint experiment involving this group and M. H. Israel, J. Klarmann, W. R. Binns (Washington University) and C. J. Waddington (University of Minnesota). HNE is designed to measure the elemental abundances of relativistic high- Z cosmic ray nuclei ($17 \leq Z \leq 130$). The results of such measurements are of significance to the studies of nucleosynthesis and stellar structures, the existence of extreme transuranic nuclei, the origin of cosmic rays, and the physical properties of the interstellar medium. HNE was successfully launched on HEAO-3 and operated until late May 1981.

The following talks and paper were presented during the reporting period:

- “Measurements of Ultraheavy Cosmic Rays with HEAO-3,” W. R. Binns et al., *For publication in Essays in Sp. Sci.* (submitted 1985).
- “Fragmentation Cross Sections of Ultraheavy Nuclei,” M. P. Kertzman et al., *Bull. of Am. Phys. Soc.* **31**, 871 (1986).
- “Elemental Abundances of Ultraheavy Cosmic Rays Measured on HEAO-3,” B. J. Newport et al., *Bull. of Am. Phys. Soc.* **31**, 871 (1986).

1.2.5. Proposal for an Advanced Composition Explorer (ACE)

This investigation, submitted to NASA for the Explorer Concept Study Program, was proposed jointly by this group, and by R. E. Gold and S. M. Krimigis (APL/JHU), G. Geiss (University of Bern), J. A. Simpson and M. E. Wiedenbeck (University of Chicago), L. F. Burlaga and T. T. von Rosenvinge (GSFC), W. C. Feldman (LANL), G. Gloeckler and G. M. Mason (UMd) and D. Hovestadt (MPI). This Explorer-class mission would make comprehensive measurements of the elemental and isotopic composition of accelerated nuclei with increased sensitivity of several orders of magnitude, and with improved mass and charge resolution. ACE would observe particles of solar, interplanetary, and galactic origins, spanning the energy range from that of the solar wind (~ 1 keV/nucleon) to galactic cosmic ray energies (several hundred MeV/nucleon). Definitive studies would be made of the abundance of essentially all isotopes from H to Zn ($1 \leq Z \leq 30$), with exploratory isotope studies extending to Zr ($Z=40$), and element studies extending to U ($Z=92$).

ACE would be a coordinated experimental and theoretical effort, designed to investigate a wide range of fundamental problems. In particular, ACE would provide the first extensive tabulation of solar *isotopic* abundances based on direct sampling of solar material and would establish the pattern of *isotopic differences* between galactic cosmic ray and solar system matter. These composition data would be used to investigate basic dynamical processes that include the formation of the solar corona, the acceleration of the solar wind, and the acceleration and propagation of energetic nuclei on the Sun, in interplanetary space, and in cosmic ray sources. They would also be used to study the history of solar system material and of galactic cosmic ray material, and to investigate the differences in their origin and evolution.

The ACE study payload includes five high resolution spectrometers, each designed to provide the ultimate charge and mass resolution in its particular energy range, and each having a collecting power 1 to 3 orders of magnitude greater than previous or planned experiments. Included in the study would be two spectrometers, a Solar Isotope Spectrometer (SIS) and a Cosmic Ray Isotope Spectrometer (CRIS), for which Caltech would play a leading role. These spectrometers would make use of the proven mass-resolution techniques and large-area detectors that were developed and tested by this laboratory over the past decade, partly through the support of this grant.

1.2.6. Galileo Heavy Ion Counter

This experiment, constructed by this group in collaboration with N. Gehrels at Goddard Space Flight Center, has been added to the Galileo mission as an engineering subsystem. It will monitor penetrating (~ 10 to ~ 200 MeV/nucleon) sulfur, oxygen, and other heavy elements in the Jovian magnetosphere with the sensitivity needed to warn of potential "single-event upsets" (SEU) in the attitude control system computer. (SEUs are state changes induced by ionizing radiation.) Caltech is responsible for management, detector testing, and calibration of the experiment, which is based on repackaging the Voyager CRS prototype unit (the PTM). Although the primary purpose is engineering support, the data will allow us to continue our investigation of spectra of trapped ions in the Jovian magnetosphere and their relation to the Jovian aurora. In addition, during cruise phase and in the outer Jovian magnetosphere, we will use the instrument to measure the elemental composition of solar flare events and of the anomalous cosmic ray component.

Current activities include response to new constraints due to mission redesign and attempting to maintain instrument reliability in the face of greatly extended ground handling.

2. Gamma Rays

This research program, which has received significant support from Caltech, is directed toward the investigation of galactic, extragalactic, and solar gamma rays with spectrometers of high angular resolution and moderate energy resolution carried on spacecraft and balloons. The main efforts have been directed toward the following two categories of experiments.

2.1. Activities in Support of or in Preparation for Spacecraft Experiments

These activities generally embrace prototypes of experiments on existing or future NASA spacecraft and they complement and/or support such experiments.

2.1.1. A Balloon-Borne Gamma Ray Imaging Payload (GRIP)

The GRIP instrument is a balloon-borne gamma-ray telescope based on a rotating coded aperture and a large area shielded NaI camera plate. Through advanced coded aperture techniques developed in this laboratory, GRIP achieves an imaging capability of 1000 0.6° pixels over a 20° field of view and a source localization capability of 3 arc minutes for 10σ sources. The energy range extends from 30 keV to 5 MeV with resolution comparable to that of the best NaI detectors (7% FWHM at 662 keV).

GRIP was readied for her maiden flight and shipped to Palestine, Texas, for launch during the fall 1985 turnaround period. Unfortunately, high altitude and/or surface conditions were unfavorable during almost the entire turnaround period, precluding a launch. The bulk of the GRIP instrument was left in storage in Palestine awaiting the next launch opportunity, while selected subsystems were returned to Caltech for enhancement. GRIP was reactivated in May of 1986 and several hardware and software modifications were integrated and tested in preparation for a fall 1986 flight. The main improvements were:

- (1) A reworked azimuthal bearing and universal joint assembly. Additional margin against possible increases in friction due to the cold vacuum of the high altitude balloon environment was obtained through careful balancing of the bearing assembly and improved lubrication of the universal joint. The average power consumption of the azimuthal torquer was reduced about fourfold.
- (2) Accurate timing capability for the measurement of pulsar periods and light curves. Modifications to the ground support hardware and software were installed to allow in-flight correlation of telemetry data with the WWVB time reference received at Palestine, Texas. A technique was developed and tested for cross-calibration of the oven-controlled crystal oscillator onboard GRIP, which serves as a time reference when GRIP is beyond telemetry range.
- (3) Source tracking algorithm improved for real time imaging. The original tracking algorithm provided updates to the telescope pointing direction once every ten minutes. While this approach was simple and adequate for the purpose of post-flight analysis, it produced a stepwise scanning motion of sources relative to the telescope field of view which was difficult to compensate for in real time. The new algorithm produces an essentially continuous source tracking telescope motion.
- (4) Weight reduction by fabrication of a new battery box.

- (5) The instrumentation of inclinometers to continuously monitor platform balance during flight and to aid in pre-flight balancing.

GRIP is shown in Figure 3 as final preparations were made for flight during the fall turnaround period of 1986. A successful 28 hour flight was obtained on October 15 and 16 (to be fully discussed in the next status report), and included observations of the quasar 3C273, the Crab and Cygnus regions, and the galactic center.

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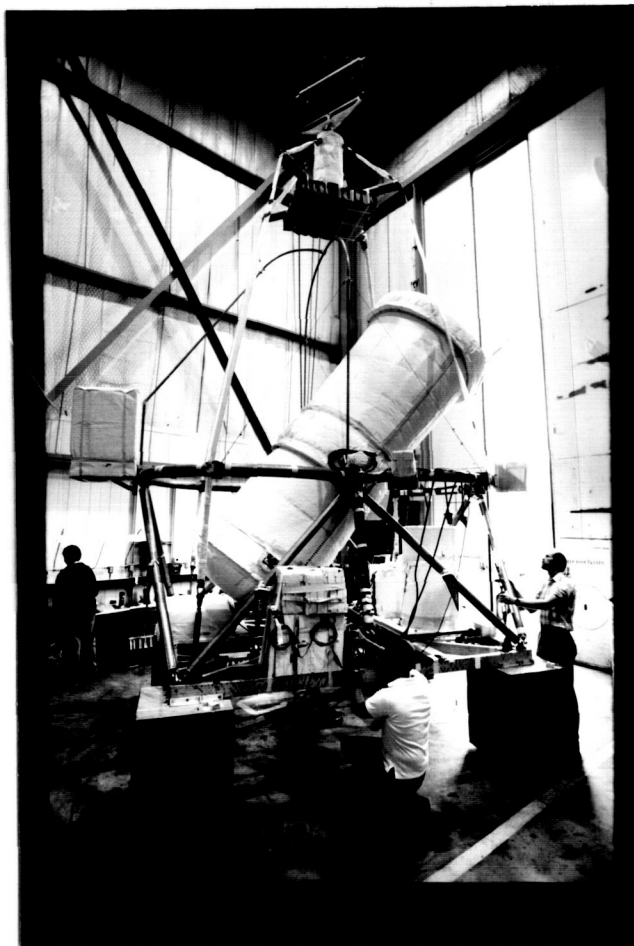


Figure 3

In the coming months we will focus attention on the strongest sources, the Crab Nebula and Cygnus X-1, and expect to obtain their spectra from 30 keV to above 1 MeV. Since the GRIP instrument monitors source flux continuously, without the need to point off-source for background measurement, we will also have the unique opportunity to study the source time variability of the black hole candidate Cyg X-1 over time scales ranging from milliseconds to hours.

2.1.2. Proposal for a Hard X-ray and Soft Gamma Ray Explorer: EXCAM (Energetic X-ray Camera)

This proposal, submitted by this group in collaboration with J. E. Grindlay (Harvard College Observatory) and S. S. Murray (Smithsonian Astrophysical Observatory), is for the study of an imaging hard X-ray and soft gamma-ray instrument for an Explorer class mission. The

instrument, called EXCAM (Energetic X-ray CAMera), uses coded aperture techniques and large-area scintillation detectors to perform high-sensitivity spectroscopy measurements with 25 arc minute angular resolution over a 10° field of view. The instrument is optimized for the energy range from 15-300 keV, with extended response up to at least 511 keV.

EXCAM would make major advances in the study of compact objects and active galactic nuclei (AGN), probing in particular the non-thermal characteristics of these sources. The mission would consist of a complete, high-sensitivity survey of the galactic plane, an all-sky survey of extragalactic and high-latitude galactic sources, and deep pointed observations of selected fields such as the rich galactic center region. The astrophysics of compact binary sources would be advanced by observations of non-thermal and high-temperature thermal emission processes from hundreds of galactic objects. Likewise, the astrophysics of active galactic nuclei and quasars would be advanced by measurements of spectra and variability in over a hundred sources, providing important clues to the nature and energetics of the central engines of these objects.

With a sensitivity ~ 10 times better than HEAO A4 in survey mode, EXCAM should identify approximately 200 AGN and over 250 galactic sources, a significant increase over the dozen AGN and ~ 50 galactic sources previously identified by HEAO A4 above 40 keV. In its deep pointed mode (10^6 s exposure), EXCAM could undertake detailed spectral studies of AGN and galactic compact objects with a flux sensitivity 100 times better than HEAO A4 at 100 keV, an energy at which spectra are known for relatively few sources. EXCAM would also significantly outperform GRO at 100 keV, having a flux sensitivity ~ 5 times better than OSSE on GRO, whose sensitivity at these energies is limited by source confusion. The total sensitivity is thus greatly increased over any previous instruments or any instrument now planned for this energy range.

2.1.3. Development of γ -Ray Imagers with Very High Angular Resolution

We have continued work on the definition of ultra-high resolution γ -ray imagers for solar and cosmic γ -ray astronomy. Above 100 keV, past instruments have been limited to a typical angular resolution of 10° or poorer. Extensions of current technology will allow γ -ray imaging with angular resolution approaching one second of arc. During the period covered by this status report, we have undertaken three activities related to the development of high-resolution γ -ray imagers.

2.1.3.1. Laboratory Studies of Fourier Transform Imaging

A practical implementation of Fourier-transform imaging techniques for high-energy photons requires a laboratory feasibility demonstration and study of imaging systematics. We have therefore constructed a prototype Fourier-transform imager. In Fourier-transform imaging, two widely-spaced, fine-scale grids create a large-scale modulation pattern of high-energy photons which can be measured with a detector having only moderate spatial resolution. This modulation pattern contains the phase and amplitude information for a single Fourier component of the source distribution. Multiple grid pairs with a variety of slit spacings and angular orientations are used to sample numerous Fourier components. An image is constructed from these Fourier components in exact analogy to multi-baseline radio interferometry.

The laboratory apparatus consisted of a set of seven subcollimator grid pairs viewed by a standard NaI scintillation camera similar to that used in the GRIP balloon instrument but thinner. The subcollimators were oriented in a single direction so that one-dimensional images are readily constructed. Two-dimensional images can also be made by simple rotation of the grid structure through discrete angular orientations.

Images of source fields containing up to 3 sources were processed using maximum likelihood and CLEAN techniques. The laboratory tests were successful in demonstrating the appli-

cation of Fourier-transform techniques to hard x-ray/ γ -ray imaging. The following talk and paper presented results from these studies:

- "A Laboratory Demonstration of High-Resolution Hard X-ray and Gamma-ray Imaging using Fourier-Transform Techniques", D. Palmer and T. A. Prince, *IEEE Trans. NS-34* (1), 71-75 (1987).

2.1.3.2. A Proposal for the Study of an Arc-Second γ -Ray Imager (GRID)

In collaboration with investigators from Univ. of Birmingham, Univ. of California at San Diego, Delft Univ., Los Alamos Scientific Laboratories, Mullard Space Science Laboratories, NASA Goddard Space Flight Center, NASA Marshall Space Flight Center, Naval Research Laboratory, Southampton Univ., and Yale, we proposed to study an Explorer-class instrument with the primary objective of high-angular resolution studies of x-ray and γ -ray emission from solar flares. Secondary objectives included high-resolution imaging and localization of galactic and extra-galactic hard x-ray and γ -ray sources. T. Prince was the lead scientist for this proposed study.

The γ -ray imager, called GRID (Gamma-ray Imaging Device) was part of a complement of instruments for precision observations of solar-flares and quiet sun activity called SHAPE (Solar High-Energy Astrophysical Plasmas Explorer). GRID is based on Fourier-transform technique similar to that studied in the laboratory tests described above.

The GRID instrument uses 34 grid-pairs to measure 34 separate Fourier components, corresponding to size scales of 1.5 arcseconds to 3 arcminutes. The grid spacings and orientations are chosen to fall on a double logarithmic spiral. The detector system is made up of modular multiwire proportional counters sensitive to x-rays from 5 to 50 keV and discrete NaI(Tl) bar detectors with energy response up to 1 MeV.

The proposal was submitted for consideration to the Explorer Concept Study Program. Efforts are also underway on a possible balloon-borne implementation of the GRID instrument.

2.1.3.3. A Proposal for Study of a High-Angular Resolution All Sky Imaging Instrument.

The ultra-high resolution γ -ray imager discussed above was designed for arc-second imaging of small ($< 1^\circ$) fields of view. In collaboration with researchers from the University of California at Berkeley (B. Sadoulet, PI and R. Lin, Co-I), we proposed to study a concept for an Explorer-class mission involving a hard x-ray/ γ -ray imager with a very large field-of-view ($\sim 2\pi$ ster), yet good angular resolution (~ 1 arc minute). Our collaborators at Berkeley have been investigating the use of gas scintillation drift chambers for detection of hard x-rays and γ -rays with excellent spatial and energy resolution. The Explorer proposal involved study of a large (1 m diameter) high-pressure spherical drift chamber as a detector. We applied our expertise in coded-aperture imaging to develop a concept for a multi-faceted geodesic dome consisting of 480 hexagonal uniformly redundant arrays (HURA's) each having approximately 100,000 holes. Such an array of coded apertures, coupled with the fine spatial resolution of the drift chamber, yields the high-performance imaging characteristics of the instrument. While the definition of such an instrument is still in the very preliminary stages, the potential is great for a wide variety of observations including those of gamma-ray bursts, AGN and diffuse background, supernovae and novae, and surveys of hard x-ray sources.

2.2. Experiments on NASA Spacecraft HEAO-3

During the past year we have reinitiated collaborative efforts with the Gamma-ray Astronomy Group at JPL on data analysis from the HEAO-3 high-resolution gamma-ray spectrometer. This work is being performed under the NASA Graduate Student Researchers Program. Christopher Starr, a graduate student in our group at Caltech, is performing detailed timing analysis of rapid variability in the gamma-ray emission (0.05-10 MeV) of black hole candidate Cygnus X-1. In addition, a search for pulsed gamma-ray emission from the pulsars PSR0950+08 and PSR1822-09 will be performed using the HEAO-3 data.

3. Other Activities

R. A. Mewaldt is serving as a member of NASA's High Energy Astrophysics Management Operations Working Group (HEAMOWG) and the Cosmic Ray Program Working Group (CRPWG). He is also a member of the Superconducting Magnet Facility (Astromag) Definition Study Team, where he is chairman of the Science and Facility Subcommittee.

T. A. Prince has received a Presidential Young Investigator Award from the National Science Foundation and is serving as a member of the Gamma-Ray Astronomy Program Working Group (GRAPWOG), the Max '91 Science Study Committee, and the Pinhole/Occulter Facility Science Working Group.

E. C. Stone continues to serve as NASA's Project Scientist for the Voyager Mission. He is also a member of the Commission on Physical Sciences, Mathematics, and Resources of the National Research Council.

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